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AN EXPERIMENTAL STUDY OF A STIFFENED FLAT STAINLESS STEEL PLATE SUBJECTED TO EXPLOSION AND STATIC LOADING

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by

K.J. Mintz*

ABSTRACT

Deflections and strains that occurred in a stiffened plate during methane/air, propane/air, and ethylene/air/oxygen explosions were measured. Static pressure measurements were also carried out before and after the methane/air explosions. The stiffener was effective at reducing the amount of deflection and strain. Failure of enclosures made of stainless steel plates are most probable at bolts or welds rather than in the plates themselves. Theories to predict elastic and permanent deflections and strains are not in accordance with the experiments: the latter are much smaller.

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ÉTUDE EXPÉRIMENTALE D'UNE PLAQUE PLANE EN ACIER INOXYDABLE
RENFORCÉE SOUMISE À UNE EXPLOSION ET À UNE CHARGE STATIQUE

par

K.J. Mintz*

RÉSUMÉ

Les flexions et les déformations qui se sont produites dans une plaque renforcée pendant des explosions méthane/air, propane/air et éthylène/air/oxygène ont été mesurées. On a mesuré aussi les flexions et les déformations qui se sont produites des charges statiques avant et après les explosions méthane/air. Le renfort était efficace pour réduire la magnitude de la flexion et de la déformation. La défaillance des contenants fabriqués en acier inoxydable risque davantage de se produire aux boulons ou aux soudures que dans la plaque elle-même. Les prédictions théoriques des flexions et des déformations élastiques et permanentes ne concordent pas avec les constatations expérimentales: ces dernières sont beaucoup moins importantes.

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CONTENTS

	<u>Page</u>
ABSTRACT	1
RÉSUMÉ	11
INTRODUCTION	1
APPARATUS	1
RESULTS	2
A. Static tests on unstressed plate	2
B. Explosion tests: methane/air	5
C. Static tests: post-explosion	7
D. Explosion tests: propane/air	8
E. Explosion tests: ethylene/air	8
F. Explosion tests: ethylene/air/oxygen	9
DISCUSSION	10
CONCLUSIONS	12
ACKNOWLEDGEMENTS	12
REFERENCES	12
APPENDIX	14

TABLES

<u>No.</u>		
1.	Static tests on stiffened flat plate	15
2.	Explosion tests on stiffened flat plate: methane/air	16
3.	Explosion tests on stiffened flat plate: methane/air	17
4.	Explosion tests: propane/air, ethylene/air and ethylene/ air/oxygen	18
5.	Centre permanent deflections	19

FIGURES

1.	Apparatus for measuring deflections and stresses	20
2.	Unstressed stiffened plate: deflections	21
3.	Unstressed stiffened plate: strains	22
4.	Unstressed stiffened plate: strains	23

Figures (Cont'd)

<u>No.</u>	<u>Page</u>
5. Unstressed stiffened plate: strains	24
6. Unstressed stiffened plate: strains	25
7. Visicorder trace of methane/air explosion	26
8. Explosion pressure vs methane concentration	27
9. Explosion time vs methane concentration	28
10. Explosion pressure vs explosion time	29
11. Cumulative permanent deflections	30
12. Elastic deflections in explosion tests	31
13. Cumulative permanent strains	32
14. Elastic strains in explosion tests	33
15. Post explosion static tests: deflections	34
16. Post explosion static tests: strains	35
17. Post explosion static tests: strains	36
18. Post explosion static tests: strains	37
19. Post explosion static tests: strains	38
20. Post explosion static tests: strains	39

INTRODUCTION

In gassy underground mines, despite sophisticated monitoring instruments, the possibility of an explosive gas mixture must still be considered. Thus, methane may enter the exhaust pipe of a diesel machine; the possibility of an ignition in the water scrubber cannot be ignored. Hence, the water scrubber must be explosion proof: it must be so constructed that it will remain intact if a methane/air explosion should occur. Some regulatory bodies require that the most severe methane/air explosion will cause no permanent deformation to an explosion proof structure. That approach may be unnecessarily severe, however, and not necessarily provide the expected safety margin.

In the first part of this study (1), it was shown that thin stainless steel plates are surprisingly strong: a clamped 3.2 mm thick plate of free area 910 x 610 mm had a maximum permanent deflection of only 47 mm at the maximum explosion pressure of methane/air. A similar plate that was welded to the sides of the explosion box had even less permanent deflection: only 21 mm.

The purpose of the present work is to extend the results to stiffened steel plates of the same dimensions and to establish, by means of stronger explosions, the safety factor.

APPARATUS

The steel box and electronic equipment were the same as in the previous study (1). A type 304 stainless steel plate, 991 x 686 mm, 6.4 mm (1/4 in.) thick, was welded to the box to give a free area of 910 x 610 mm (36 x 24 in.). The weld, which was on the inside of the box, was a full fillet type with 5 mm (3/16 in.) legs, continuous on all four sides. Two 50 x 50 x 10 mm (2" x 2" x 3/8") steel angles were welded to the inside of the plate in a toe-to-toe pattern with a 6 mm (1/4 in.) continuous fillet weld. The position of the strain gauges and displacement transducers are shown in Fig. 1.

RESULTS AND DISCUSSION

Part A. Static Tests on Unstressed Plate

Seven separate runs were carried out to measure deflection and strain as a function of static pressure. Dry compressed air was used to pressurize the explosion box; the maximum pressure used was well below the estimated yield point. The uncertainties due to drift are ca. ± 0.02 mm in deflection and ca. $\pm 2\mu$ in strain. The data in Fig. 2-6 indicate that these measurements are quite reproducible. In this pressure range, all the data fall on straight lines within the experimental error. The least-squares slopes and standard deviations are given in Table 1.

Deflections

The fact that the deflection is greater at station B than at station A indicates that the stiffener has a significant effect. The stiffener is not sufficiently rigid, however, that the plate can be considered to be divided into two smaller plates.

A theoretical formula, Equation 1, in widespread use, relates the deflection, w , to the applied pressure P , and the dimensions of a rectangular plate. The formula is derived assuming: small deflections below the elastic limit, a plate rigidly fixed on all sides, and a uniformly applied pressure.

$$w = k_D \frac{P a^4}{E t^3} \quad [1]$$

where a is the length of the short side,
 t is the thickness

The coefficient k_D , is a function only of the ratio of the short and long sides of the rectangle; it varies from 0.014 for a square to 0.028 for an infinitely long rectangle (2). Equation 1 predicts that, for a given plate, a plot of deflection vs pressure is a straight line, which agrees with our experiments.

In our earlier study (1), the experimental value of k_D for a clamped plate of the same dimensions was found to be 0.019, significantly lower than the theoretical value of 0.024. An early experimental study by Laws (3), however, yielded a value of 0.020. This was in good agreement with our work.

Experiments on thinner plates (1) indicate that welded plates undergo less deflection than clamped plates.

If Equation 1 were used to calculate k_D from the experimental data at station A (i.e., neglecting the stiffener completely), its value would be 0.0020, exactly one-tenth of the 'true' value. On the other hand, if the stiffener were considered to be perfectly stiff, then each half, 405 x 610 mm (16 x 24 in.), could be treated as a separate plate fixed on all edges. Using the data at station B and Equation 1, $k_D = 0.0203$, which is the expected value. Hence, although the stiffener does bend under pressure, it keeps the centre line of the plate sufficiently rigid that the half plates can be considered to have fixed edges.

Strains

According to theory, the strains in a flat plate, ϵ , fixed on all sides can be expressed in the form:

$$\epsilon = k \frac{P a^2}{E t^2} \quad [2]$$

The value of the stress coefficients, k , are functions of the ratio of the long to short sides and the location in the plate. The maximum stress should occur at the middle of the long side. The experimental values previously determined on a 6.4 mm (1/4 in.) thick plate were not in good agreement with the theoretical values (2):

	<u>experimental</u>	<u>theoretical</u>
middle of the long edge	-0.25	-0.45
centre (parallel to short edge)	+0.13	+0.22
middle of the short edge	-0.23	-0.34

However, the value measured by Laws (4), for the middle of the long edge, -.21, is in reasonably good agreement with ours.

If the effect of the stiffener is neglected, then the experimental data can be used to calculate k , using $a = 610$ mm in Equation 2, viz, $k_1 = 0.010$, $k_2 = 0.034$, $k_{12} = -0.032$. (The subscripts refer to the station number in Fig. 1). Not only are these values much smaller than those

measured for a non stiffened plate (see text above), but k_1 has the opposite sign.

If the stiffener were considered to be perfectly effective at fixing the 'edge' of the half plate, Equation 2 could be used with: $a = 406$ mm, which yields $k_{12} = -0.073$, $k_{11} = +0.101$, $k_9 = -0.109$. These coefficients have the correct sign, and the values are much closer to the experimental values quoted above. Hence, the strain data corroborate the conclusion based on the deflection data that the half-plates can be considered to have fixed edges (to a first approximation).

Using the half-plate concept, the strain at station 10 should be, by theory, (2), 0.55 of the strain at station 11. The experimental ratio is somewhat lower, viz, 0.39. Conversely, comparing station 10 to station 9, the theoretical ratio of -0.36 is the same as the experimental.

The strain gauges at stations 3,4,5 are located on the free area of the plate just outside the area of the weld. (The experimental data are shown in Fig. 4). Three gauges are required for determining the principal stresses and their directions (see Appendix A). As it turns out, the maximum stress is virtually coincidental with station 4 (the difference is only 3° , which is within the experimental uncertainty). Note that the maximum stress is negative, which is expected near a fixed edge.

Using Equation 2 and assuming the stiffener is completely effective, then $k_4 = -0.107$. It should be equal to k_{12} (-0.073); however, as noted above, k_{12} is somewhat smaller than the expected value of -0.25. By symmetry, the strain at station 3 should be the same as at station 5. Although the former is twice the latter, the rather small values involved coupled with slight variations in the width of the weld make this disagreement unimportant.

For the middle of a fixed edge, the stress parallel to the edge should be 0.3 (Poisson's ratio) times the stress perpendicular to the edge and have the same sign. In fact, using the equations in Appendix A, the ratio is -0.55 (note the change in sign). The values of the strain at this point just outside the weld area are only slightly less than at station 2, located over the centre of the stiffeners. Hence, the strain at station 2 can be treated as due to the motion of the plate as a whole rather than localized on the stiffener.

Figure 6 shows the strains at stations 6,7,8, the corner of the stiffener and the side of the plate. These strains are very small, as expected in a rigid corner. In fact, because the strain gauges occupy a finite space, the true strains at the very corner would be even smaller. The analysis into principal axes (Appendix A) indicates that the values of station 7 are very close to those of the principal strain. The angle of the principal axis is approximately 35° to the stiffener, compared to the expected value of 37° which is calculated assuming that the principal axis points toward the centre.

Although two of the three corner strains (stations 13 and 15) were extremely small, as expected ($-5 \mu\text{strain}$ at 100 kPa), the strain at station 14 was surprisingly large (see Fig. 6). The reason for that is not known. Two separate runs were carried out; the data was reproducible. There was no permanent strain upon removing the pressure. Unfortunately, it cannot be determined if this anomaly is real or merely due to a difficulty with the strain gauge.

Part B. Explosion Tests: Methane/Air

Figure 7 shows the output from the Visicorder for trial No. 9. The discharge of the spark plug causes a sharp momentary pulse to be picked up by the Visicorder, thus producing a reference point. After $\sim 40 \text{ ms}$, the pressure begins to rise; shortly thereafter, deflections and strains begin to occur. The maxima of all the curves occur within about 10 ms of each other. The strains at stations 4 and 9 are negative, hence, the curves are in the reverse direction. The rate at which the curves decrease after their maxima is dependent on the leakiness of the box. After a few minutes, the valves to the box are opened to relieve the pressure. The deflections and strains do not immediately reach their steady-state values, however, because the plate is still warm from the explosion. The box is flushed with cool, dry air for at least one hour. Even after this, the strain gauges may still be changing slightly for two hours or more. This delay in reaching the final value causes an additional uncertainty because of the random drift that always occurs with the strain gauges. The permanent deflections, unlike the other parameters, are measured using a precision voltmeter so as to obtain more accurate readings than can be obtained from the Visicorder chart.

Pressure and time

The measured maximum pressure detected by the strain-gauge pressure transducer was plotted as a function of the methane concentration (Fig. 8). The results of earlier trials are also included. The peak is broad; the maximum is about 620 kPa at about 9.5% methane.

A similar plot of the time from ignition of the spark plug to the maximum pressure is plotted against the methane concentration (Fig. 9). The minimum time to explosion is about 0.45 s, occurring at about 9.5% methane.

The scatter is reduced significantly when maximum pressure is plotted against time-to-explosion (Fig. 10), which indicates that the scatter is not primarily due to error in measuring either of those parameters. If the scatter were due to uncertainty in the measurement of the concentration, then there should have been little scatter around 9.5% CH₄ in Fig. 8 and 9 (because neither independent variable is affected very much by concentration between 9 and 10% methane). Since this is not the case, the explosions appear to have varied in intensity in some random manner, for a reason not understood.

Deflection

The permanent deflection in each trial along with the cumulative permanent deflections are given in Table 2. A plot of the latter parameter for both stations A and B shows that it can be represented adequately in this pressure range by a straight line (Fig. 11). Both lines intercept the X-axis at 260 kPa; presumably that would be the maximum pressure at which no permanent deflection would occur. Additional explosion tests at the optimum concentration do not produce further significant permanent deflection. Note that the permanent deflection is greater at station A than at station B, the opposite of the elastic deflections (both in static and explosion trials). The deflections at stations A and B are strongly correlated (the coefficient, $r^2 = 0.9998$).

The elastic deflection is defined as total minus the permanent. The curve for each set of points is constrained to pass through the origin to make it physically reasonable. For station A it is a straight line, but for station B, it bends over at high pressures. For comparison, the extrapolation of the straight lines obtained from the static tests on the unstressed plate are also shown. Surprisingly, there is little difference between the static and explosion elastic deflections.

Strains

As mentioned above, the measurement of the permanent strains is limited by the drift; hence, the accuracy is estimated to be $\sim \pm 10 \mu$ strain in each trial. As a result, the "cumulative permanent μ strain" shown in Table 3 must be interpreted with some caution. The final value of $+60 \mu$ strain for station 11 (the centre of the 'half-plate') is composed of a series of 10μ strain changes; thus, it is close to zero within the experimental uncertainty. This is rather surprising since there was concurrently permanent deflection at that point (station B).

The cumulative permanent strains at stations 4 and 9 are shown in Fig. 13. Note that the permanent strains at station 4 are positive, even though the total strains are negative. This effect is probably due to the influence of the stiffener: recall that the permanent deflection at station A is greater than at station B. The largest permanent strain occurs at station 9, as expected.

In the earlier study on the unstiffened plate of the same thickness, the maximum cumulative strain was -1440 , and the cumulative deflection, 15 mm. The stiffened plate produces roughly $1/4$ of those values when subjected to the same strength of explosion.

Applying the formula that elastic strain = total strain - permanent strain leads to the anomaly for station 4 that elastic strain is greater than the total strain. Nevertheless, these data are plotted and compared to the extrapolation of the pre-explosion static tests (Fig. 14). The order of the magnitudes of the strains is different from the pre-explosion tests, with the maximum strain now at the centre of the 'half-plate'.

C. Static Tests: Post-explosion

Following the explosion tests with methane/air, a complete set of static tests similar to those in part A were carried out. The only difference is that the elastic region is much greater, up to about 600 kPa.

The deflections are shown on Fig. 15. At station A, the slope of the line is slightly less than in the pre-explosion tests. For station B, the data lie on a curve rather than a straight line. The initial slope is somewhat greater than in the pre-explosion tests. This result may seem surprising: in the previous tests without stiffeners, the slopes decreased substantially after the explosion.

The strains are shown in Fig. 16-20 as a function of pressure. Most of the curves are concave downward as expected, though some are concave upward. The initial slopes are shown in Table 1. Most of the values are very close to the pre-explosion static tests. The larger slopes at stations 10 and 11, however, are in accordance with the larger deflection-pressure slope at station B. Thus, this unexpected phenomenon appears to be real. It is probably not due to the characteristics of the metal at the point itself, but to the geometry of the distorted plate. As can be seen very clearly in Fig. 12, the elastic deflection-pressure curve at station B decreases in slope once the total deflection at station B becomes greater than at station A.

The reason for the generally small changes in slopes after the explosion tests, compared to the previous work on unstiffened plates, is due to the much smaller amount of permanent deflection and strains (less work-hardening). At stations 12 and 14, some decrease in slope did occur, which is probably where the greatest permanent strain had occurred in the explosion tests.

D. Explosion Tests: Propane/Air

In order to establish a safety margin on the strength of the plate, a propane/air mixture, which produces a stronger explosion, was used. As expected, the maximum pressure during the explosion was higher and the time to reach the maximum pressure was smaller than for the methane/air tests (trials B1-B4 in Table 4). The additional cumulative permanent deflections were within the error limits of the lines established for methane/air (Fig. 11). The elastic component of the deflection at station B, however, was slightly higher than predicted by an extrapolation of the curve in Fig. 12. Very little, if any, additional permanent strain occurred at stations 4,9,11. The elastic strains for stations 9 and 11 were slightly higher than predicted by extrapolations of the curves in Fig. 14.

E. Explosion Tests: Ethylene/Air

Further tests were carried out with optimum mixtures of ethylene/air (trials C1-C3 in Table 4). Although the explosion pressure was only slightly higher, the time to explosion was much shorter. Both the cumulative, permanent and the elastic deflections were slightly greater than the extrapolated

curves (Fig. 11 and 12). This difference is probably due to the dynamic effect of the explosion. Even including this effect, it is clear that the plate was in no danger of breaking.

F. Explosion Tests: Ethylene/Air/Oxygen

To further increase the severity of the test, oxygen-enriched mixtures of ethylene/air were used (trials D1-D3 in Table 4). The concentrations of the gases were only very approximate. The enrichment caused a significant increase in explosion pressure and a marked decrease in time to maximum pressure. The permanent and elastic deflections were increased once again.

The final test was a stoichiometric mixture of ethylene/oxygen (1:3 by volume). This mixture detonated. Although the stiffened plate being tested was not destroyed, the bolts holding a flat plate on the bottom of the test box were sheared off by the force of the explosion. The plate was recovered intact. The resultant rapid propulsion of the whole box cut the wires connecting the transducer and strain gauges to the Visicorder, so that no measurements could be obtained. (The explosion time was < 0.01 s, the traces on the visicorder were all off scale; thus pressure > 1000 kPa, strains $> 3000\mu$ and deflections > 20 mm.) After the tests, the welds holding the plate to the box and the stiffeners to the plate were still intact. The total permanent deflections at stations A and B were, respectively, 21.2 and 11.5 mm. Taking into account the deflections from the previous tests, the additional deflections due to the detonation were 14.8 and 5.0 mm, respectively.

On each of the other five sides of the test box, a plate (6.4 mm thick) had been clamped in place throughout all the tests. After the detonation, the centre deflections were measured (see Table 5). Although a portion of the deflections probably occurred during the pre-detonation trials, the predominant portions, particularly for the smaller plates, were caused by the detonation.

DISCUSSION

Zebetakis (5) has quoted a formula:

$$t = 75 \frac{3}{\sqrt{V}} \quad [3]$$

which relates the time to maximum pressure, t (in ms), to the volume of the enclosure in ft^3 , V . He states that Equation 3 is valid for paraffins (presumably the equation is empirical). For the size of enclosure used in our study, 0.44 m^3 (13 ft^3), Equation 3 predicts $t = 180 \text{ ms}$. The minimum values obtained were 420 and 310 ms for methane and propane, respectively. One of the reasons for the discrepancy is that Equation 3 applies to explosions ignited in the centre and in our apparatus, the spark plug is on the side. Bartknecht (6), for a vessel of 1 m^3 , gives 370 ms for the minimum time for a propane/air mixture, which is in good agreement with our value.

Bartknecht (6) defines explosion violence as the maximum rate of pressure rise, dp/dt , and relates it to the volume of the enclosure:

$$dp/dt = K_G V^{-1/3} \quad [4]$$

Using his values of K_G , Eq [4] predicts that for our enclosure, $dp/dt = 7.3 \text{ kPa/ms}$ and 10 kPa/ms for methane and propane, respectively. From the Visicorder graphs, the experimental values are roughly half the predicted values. On the other hand, Cox and Scott's value (7) is much higher than predicted by Equation 4 (63 kPa/ms vs 27 kPa/ms).

On the propane/air explosion Visicorder curves in particular, distinct changes in slopes were noticed about 0.5 s before the peak pressure. These breaks are suspected to be due to the flame front reaching the walls.

Cox and Scott (7) have published formulae for calculating the permanent deflections of flat plates. In our previous study, the permanent deflection (from explosion tests) was observed to be much less than predicted by Equation 6 of Ref. 7, which is for static loadings. (Dynamic effects would increase the predicted deflection.) The relationship between permanent deflection and pressure is predicted by that equation for a given plate to be

a straight line. Both in our earlier tests on the unstiffened plate and in the current study, the graphs of cumulative permanent deflection are straight lines (Fig. 11) provided that the deflection is not too great.

Although the pressure in the detonation trial was not measured, Equation 6 of Ref. 7 can be used to estimate an upper limit of the pressure from the deflection data. (The actual pressure should be lower because of dynamic effects.) These are shown in the last column in Table 5. The first value is much lower than the others because no account was taken of the stiffener. But the other pressures are also much lower than expected for a detonation. This is in accordance with our previous conclusion that the Cox and Scott equation grossly overestimates the deflections because it is based on a rigid-perfectly plastic theory. Moreover, the wide scatter of pressures indicates that the equation is not valid even as a relative measure for plates of different free areas and the same thickness.

The current Mine Safety and Health Administration (U.S.) regulation is that the permanent deformation be less than 0.040 in/ft of span (3 mm/m). The smallest plate (No. 6) meets that requirement even after the detonation. Although the stiffened plate does not meet the above requirement for methane/air explosions, the fact that it withstood a detonation indicates that the rule provides a wide margin of safety for this type of plate.

The amount of permanent deformation can be reduced by pre-stressing the plate. (Pre-stressing will also increase the maximum pressure at which permanent deformation does not occur). Indeed, this procedure has been proposed recently to allow thin-walled flame-proof electrical enclosures to pass tests requiring no permanent deformations (8). Excessive pre-stressing, however, can reduce the safety factor (i.e., the plate becomes more brittle), so that a rule providing for an allowable permanent deformation does not yield the same safety margin for all plates. Moreover, the instantaneous deformation is probably more important than the permanent deformation, albeit more difficult to measure.

The fact that none of the stainless steel plates could be made to rupture indicates that the potential problems lie not so much with the plates themselves, but rather with the means of attaching them, i.e., the bolts or the welds.

CONCLUSIONS

1. The stiffener acts to prevent large deflections and strains from occurring.
2. The safety factor on this size and thickness of plate is at least 10.
3. The stiffener makes the centre line of the plate sufficiently rigid that as a first approximation, each half can be considered as a separate plate with fixed edges.
4. The theories to predict both elastic and permanent deflections are not in good agreement with the experimental values (these err on the conservative side).
5. Bolts and welds are the critical points of enclosures made of stainless steel plates, rather than the plates themselves.

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APPENDIX

To determine the principal stresses in a location where the principal axes are not known, it is necessary to install three strain gauges: the second at an angle 45° to the first, the third at an angle 45° to the second. Strain-gauge manufacturers sell the three as a single unit for ease in installation.

If ϵ_a , ϵ_b , ϵ_c are the experimental strains and ϵ_c is 90° counterclockwise from ϵ_a , then the principal strains, ϵ_1 and ϵ_2 are given by:

$$\epsilon_{1,2} = 1/2 \left\{ \epsilon_a + \epsilon_c \pm \left[2(\epsilon_a - \epsilon_b)^2 + (\epsilon_b - \epsilon_c)^2 \right]^{1/2} \right\}$$

The angle that the principal strain, ϵ_1 , makes with the experimental strain, ϵ_a , is given by:

$$\theta = 1/2 \tan^{-1} [(2 \epsilon_b - \epsilon_a - \epsilon_c) / (\epsilon_a - \epsilon_c)]$$

The principal stresses, σ_1 and σ_2 are given by:

$$\sigma_{1,2} = 0.5 E (1 - \nu^2)^{-1} \left\{ (1 + \nu)(\epsilon_a + \epsilon_c) \pm (1 - \nu) \left[2(\epsilon_a - \epsilon_b)^2 + (\epsilon_b - \epsilon_c)^2 \right]^{1/2} \right\}$$

Table 1 - Static tests on stiffened flat plate

	Slope (mm/kPa or μ strain/kPa)	
	<u>Pre-explosion</u>	<u>Post-explosion</u>
<u>Deflection</u>		
Station A	0.0054 $\pm$.0001	0.0050 $\pm$.0001
Station B	0.0108 $\pm$.0001	0.0124 $\pm$.0004
<u>Strain</u>		
Station 1	0.46 $\pm$.01	0.46 $\pm$.01
2	1.57 $\pm$.01	1.44 $\pm$.01
3	-0.29 $\pm$.01	-0.32 $\pm$.02
4	-2.19 $\pm$.03	-2.13 $\pm$.03
5	-0.70 $\pm$.01	-0.72 $\pm$.02
6	0.14 $\pm$.01	0.18 $\pm$.03
7	-0.31 $\pm$.01	-0.28 $\pm$.02
8	-0.10 $\pm$.01	-0.06 $\pm$.02
9	-2.24 $\pm$.01	-2.26 $\pm$.02
10	0.81 $\pm$.01	1.01 $\pm$.01
11	2.06 $\pm$.01	2.19 $\pm$.05
12	-1.50 $\pm$.01	-1.37 $\pm$.02
13	-0.04 $\pm$.01	-0.09 $\pm$.02
14	-1.51 $\pm$.01	-1.30 $\pm$.02
15	-0.04 $\pm$.01	-0.09 $\pm$.02

Note: Error limits are standard deviations

Table 2 - Explosion tests: methane/air, deflections

Trial No.	CH ₄	Time (s)	Max. P(kPa)	Deflection (mm)					
				Permanent				Elastic	
				Stn. A		Stn. B		Stn. A	Stn. B
				in trial	cum.	in trial	cum.		
1	6.1	1.37	382	1.24	1.24	0.94	0.94	1.85	4.50
2	7.0	0.79	438	0.94	2.18	0.76	1.70	2.31	5.21
3	8.0	0.55	~520	0.84	3.02	0.74	2.44	2.87	5.87
4	9.0	0.44	612	0.71	3.73	0.61	3.05	2.97	6.22
5	9.6	0.44	624	0.30	4.03	0.20	3.25	3.07	6.32
6	9.8	0.43	639	0.28	4.31	0.18	3.43	3.33	6.35
7	9.8	0.47	607	0.03	4.34	0.05	3.48	3.10	6.20
8	9.8	0.42	626	0.03	4.37	0.05	3.53	3.12	6.25
9	9.9	0.42	620	0.03	4.40	0.03	3.56	3.30	6.05

Table 3 - Explosion tests: methane/air strains

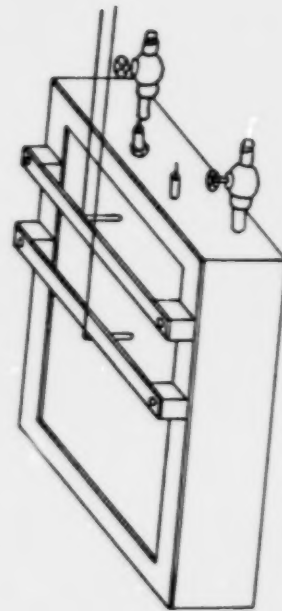
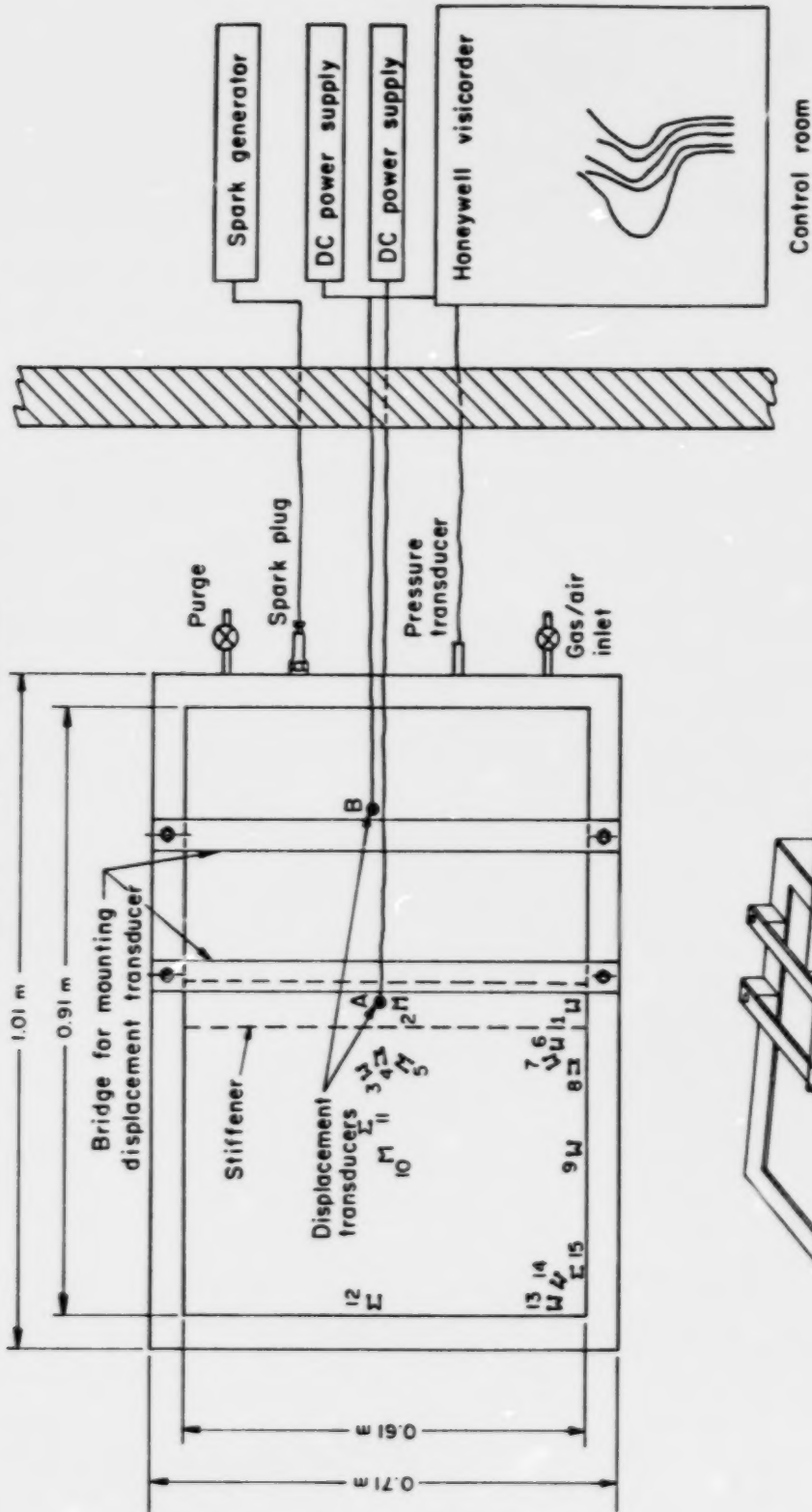
Trial	Permanent μ strain						Total μ strain		
	Stn. 11		Stn. 4		Stn. 9		Stn. 11	Stn. 4	Stn. 9
No.	In trial	cum	In trial	cum	In trial	cum			
1	-10	-10	60	60	-160	-160	860	-610	-880
2	+10	0	60	120	-70	-230	1060	-730	-980
3	-10	-10	20	140	-100	-330	1210	-800	-1070
4	+20	+10	40	180	0	-330	1300	-840	-1100
5	+10	+30	0	180	-20	-350	1300	-820	-1100
6	+10	+40	10	190	+10	-340	1330	-830	-1120
7	+10	+50	-10	180	+20	-320	1280	-800	-1060
8	+10	+60	20	200	+20	-300	1300	-820	-1090
9	0	+60	10	210	+10	-290	1290	-810	-1070

Table 5 - Centre permanent deflections

Size of free area	Deflection	Calc. P*
(mm)	(mm)	(kPa)
1. 610 x 910	21.2	565
2. 460 x 610	24.7	1200
3. 305 x 610	23.2	2210
4. 305 x 305	10.5	1780
5. 230 x 760	13.6	2340
6. 160 x 760	2.1	1580

* By Eq [6] of Ref. 7

SCHEMATIC DIAGRAM



PICTORIAL VIEW

Fig. 1 - Apparatus for measuring deflections and stresses

FIG.2.UNSTRESSED STIFFENED PLATE-DEFLECTIONS

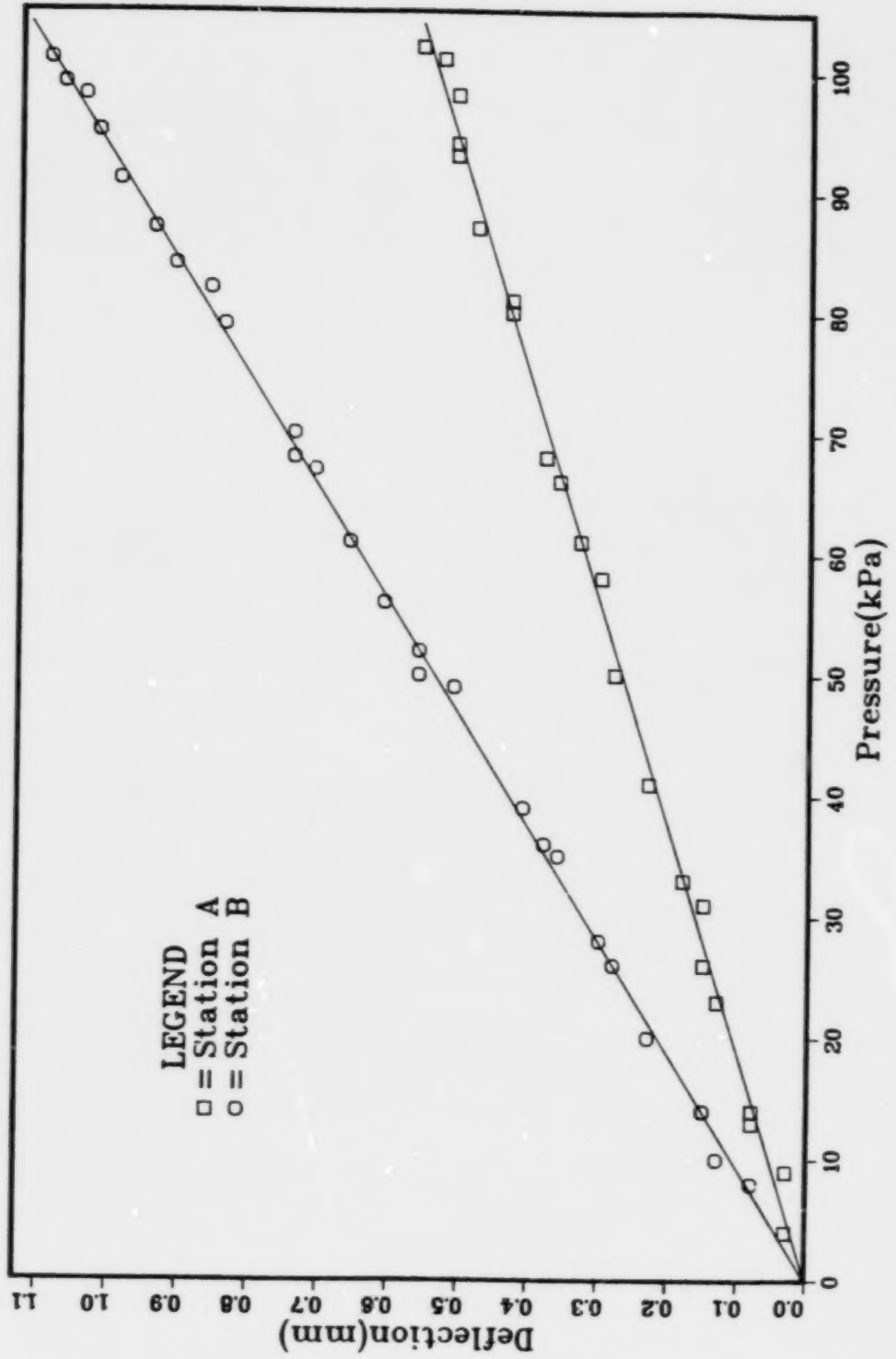


FIG.3.UNSTRESSED STIFFENED PLATE-STRAINS

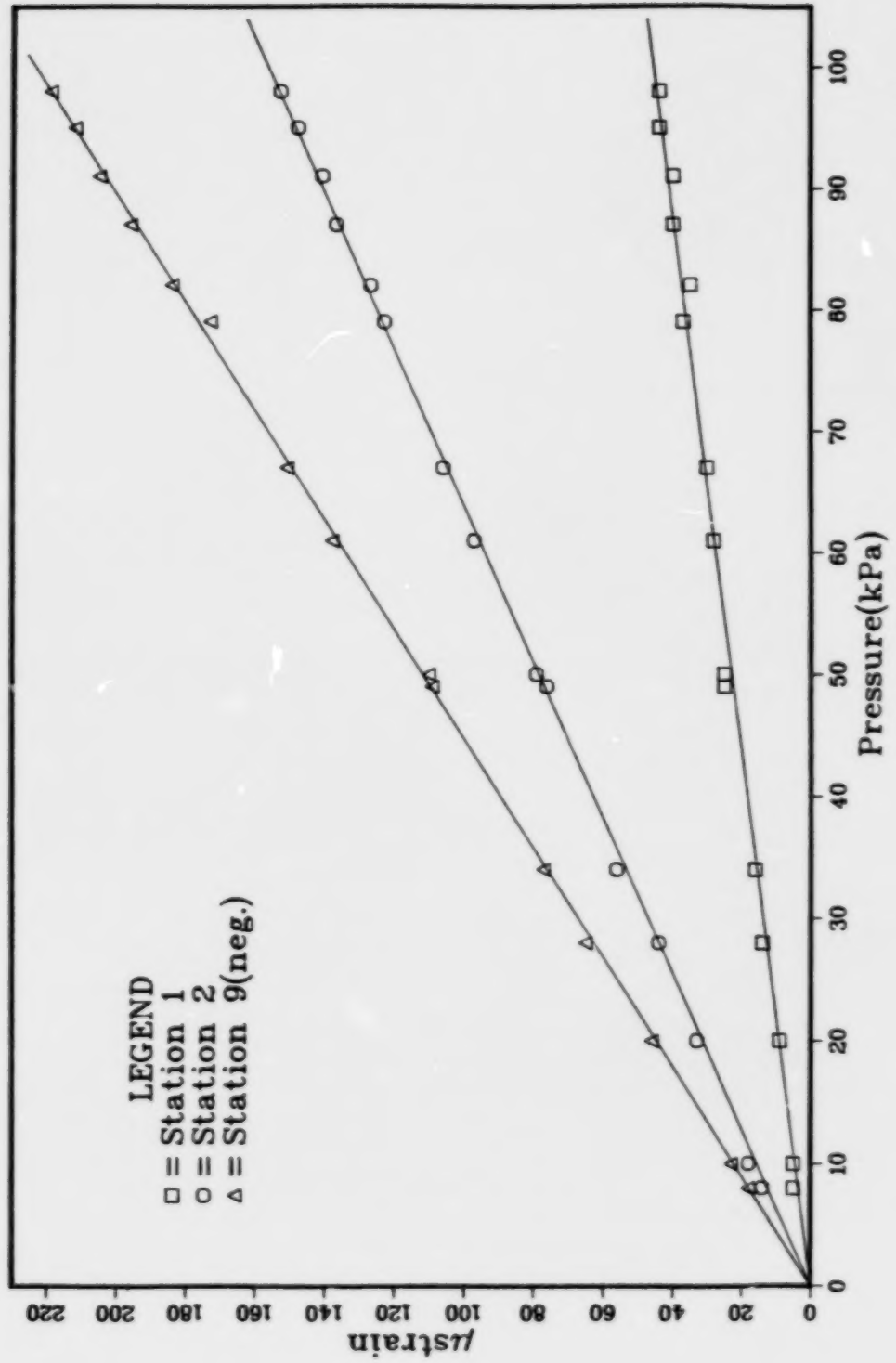


FIG.4.UNSTRESSED STIFFENED PLATE-STRAINS

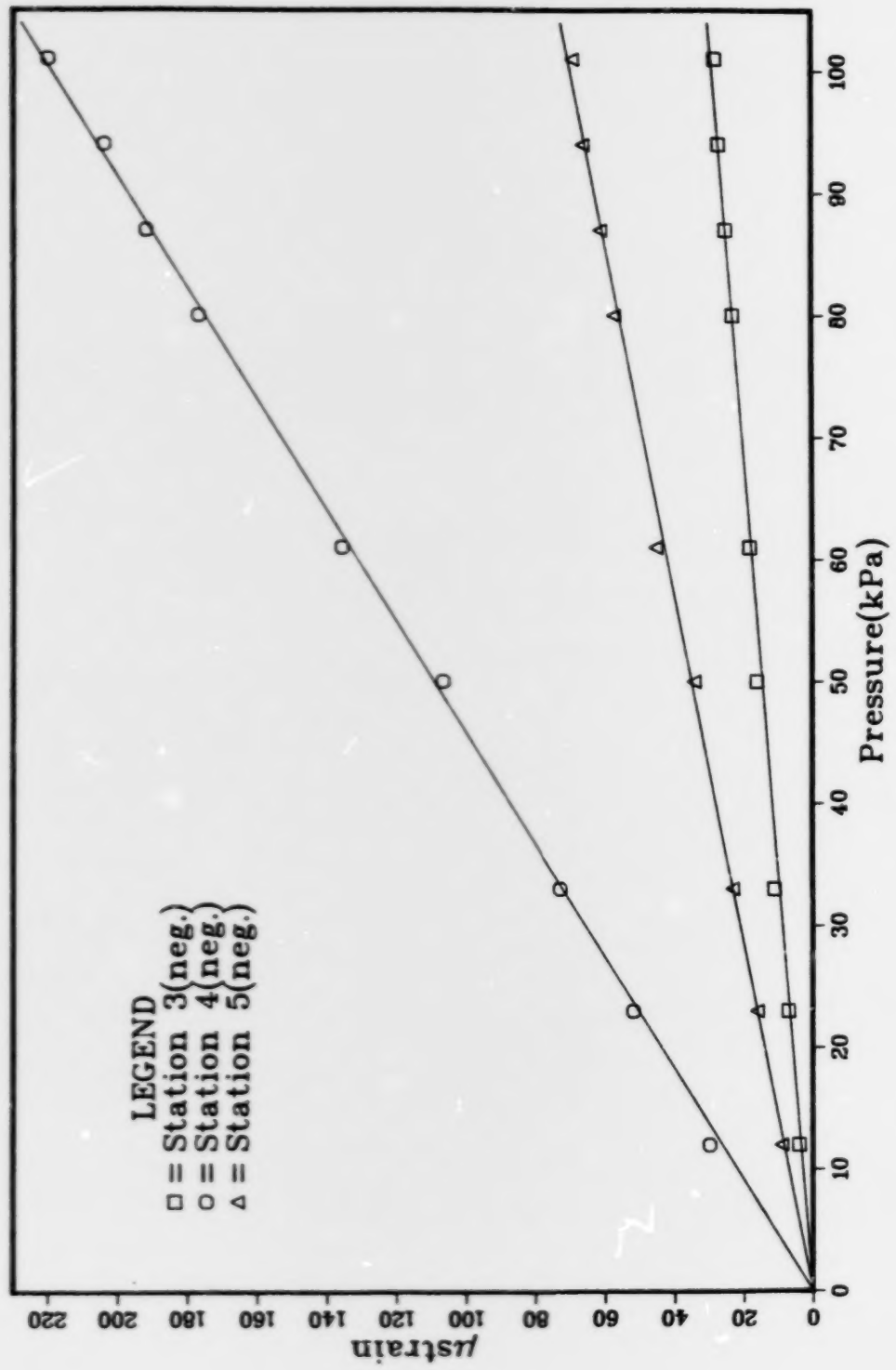


FIG.5.UNSTRESSED STIFFENED PLATE-STRAINS

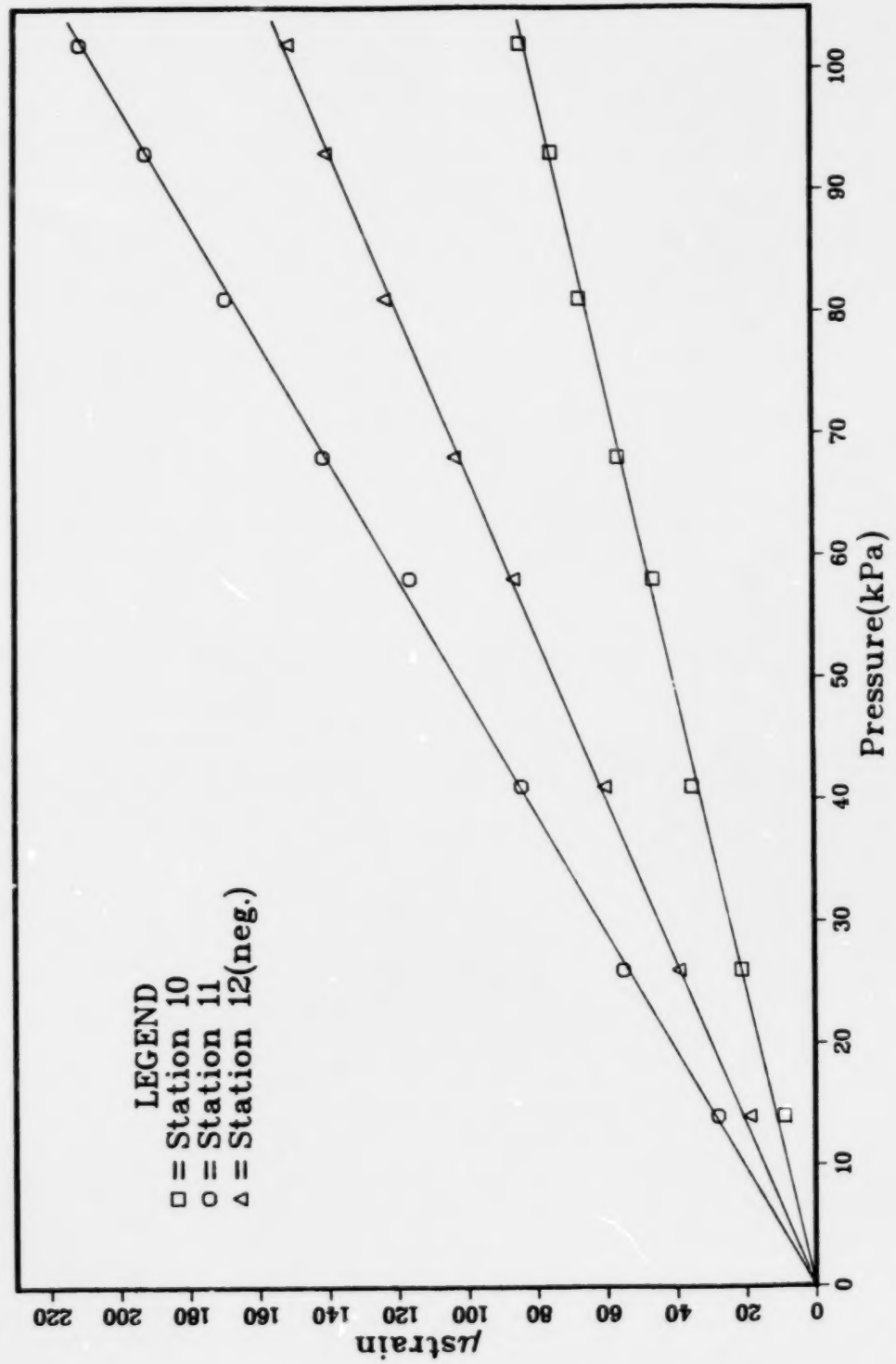
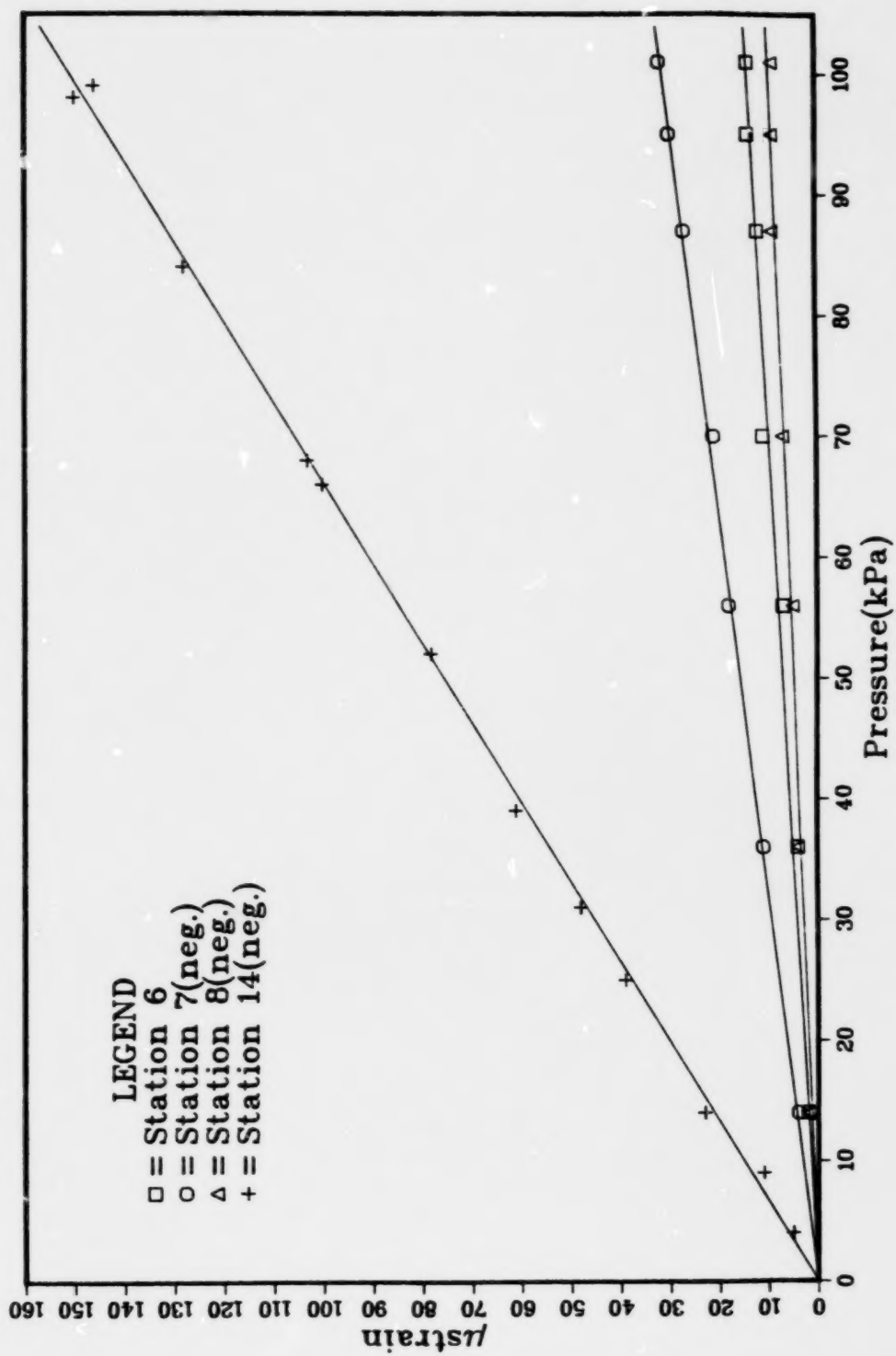


FIG.6.UNSTRESSED STIFFENED PLATE-STRAINS



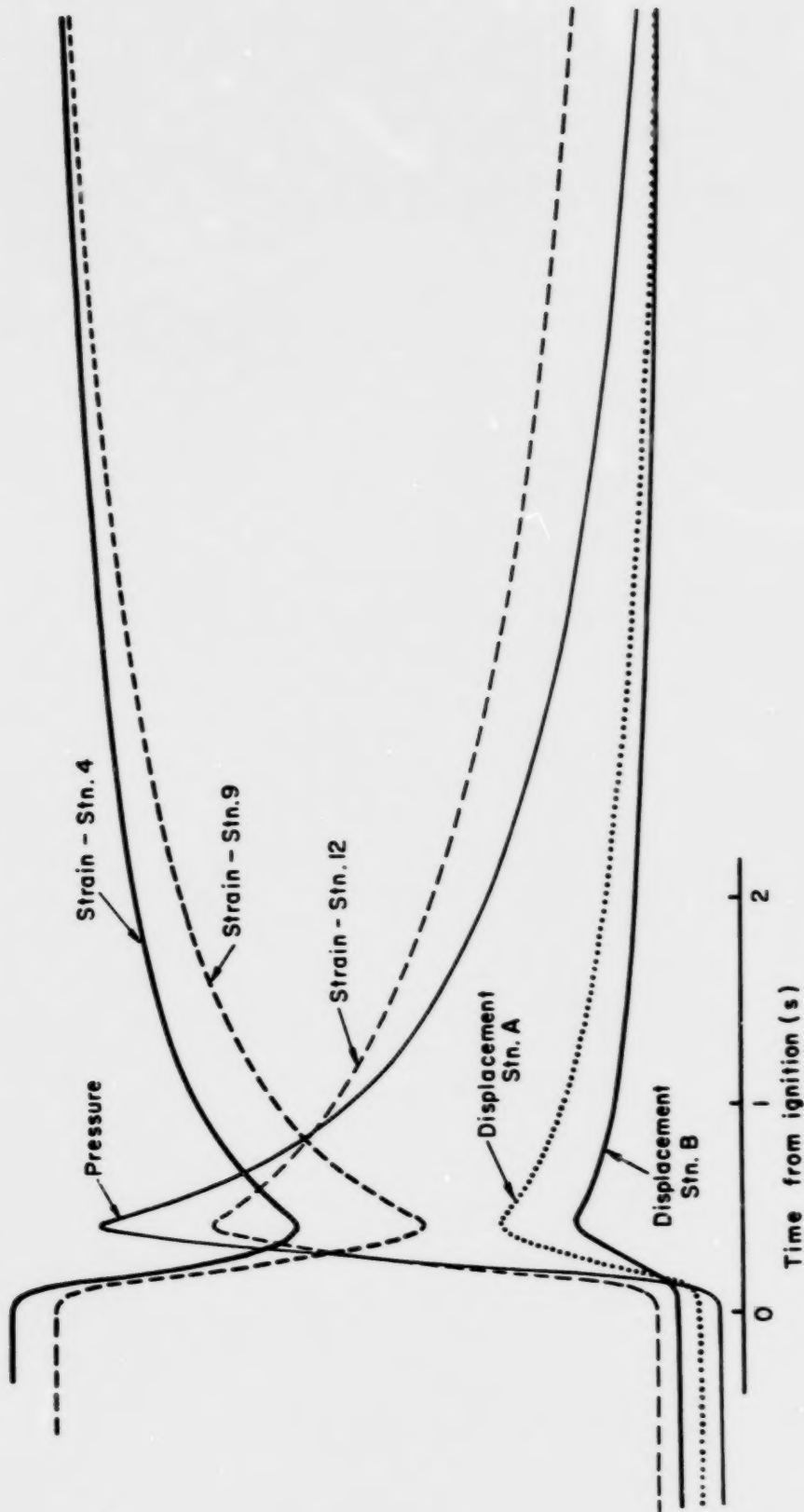


Fig. 7 - Visicorder trace of methane/air explosion

FIG.8.EXPLOSION TESTS:
PRESSURE VS. CONCENTRATION

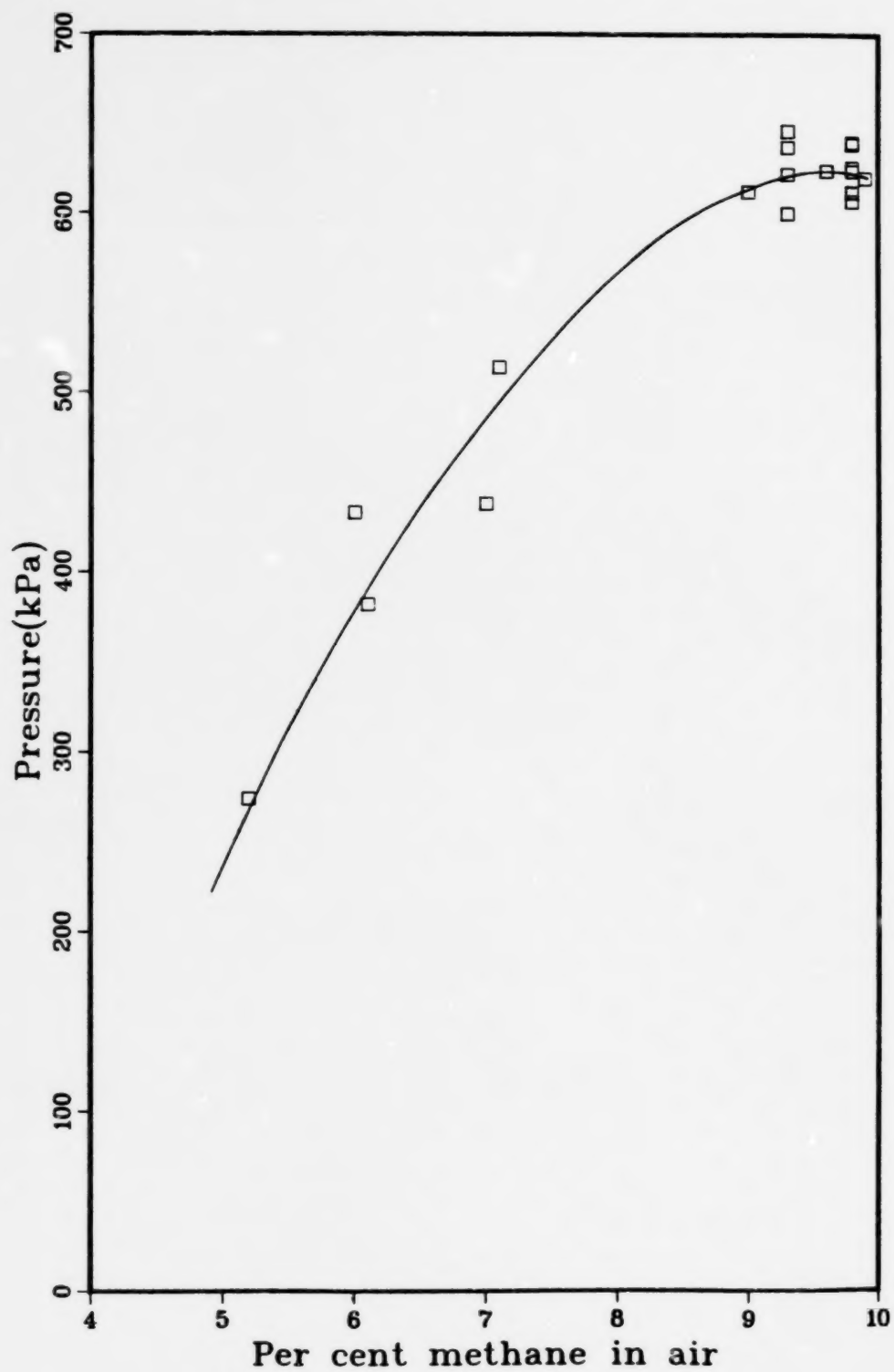


FIG.9.EXPLOSION TESTS:
EXPLOSION TIME VS. CONCENTRATION

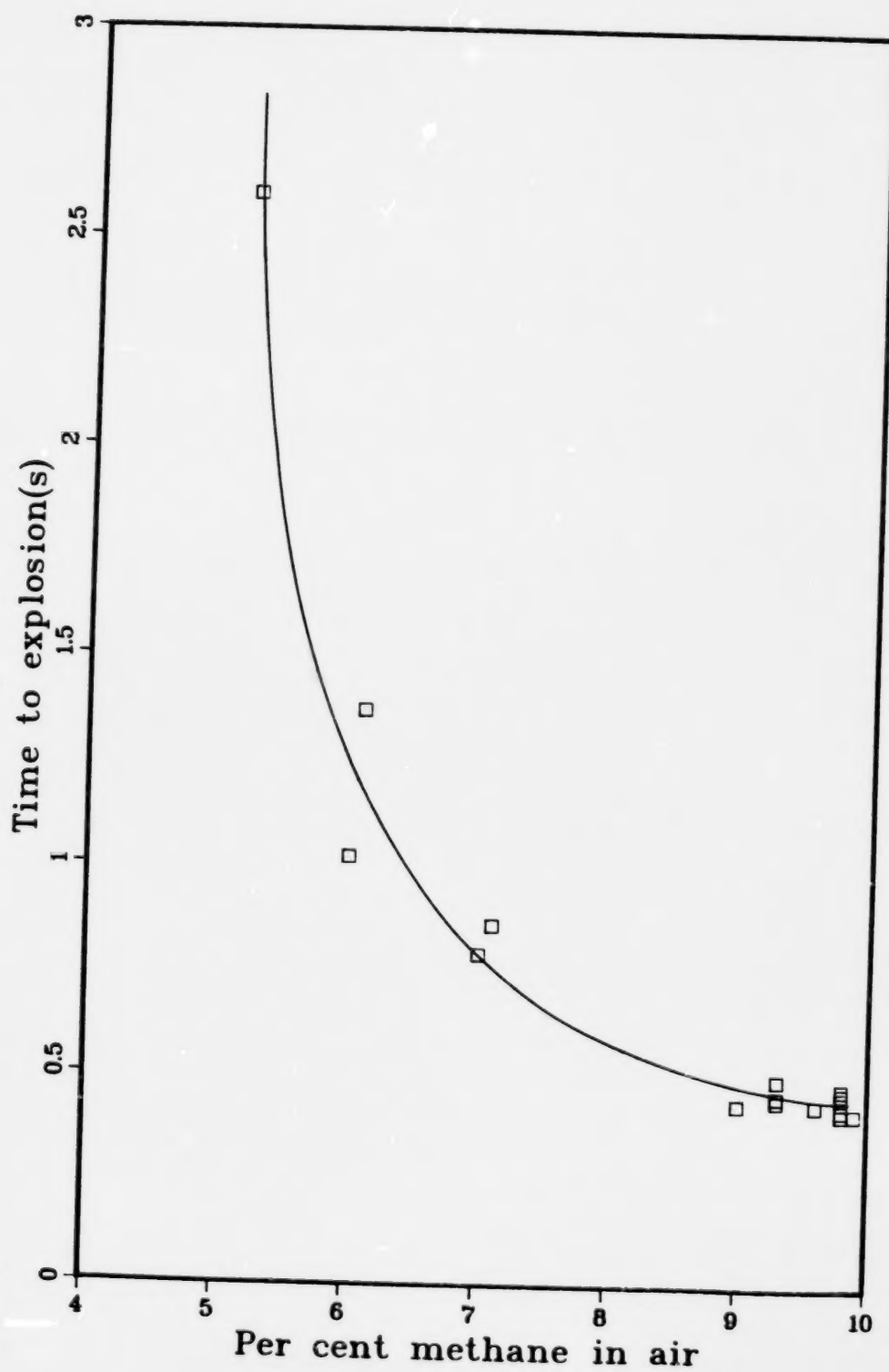


FIG.10.EXPLOSION TESTS:

PRESSURE VS. EXPLOSION TIME

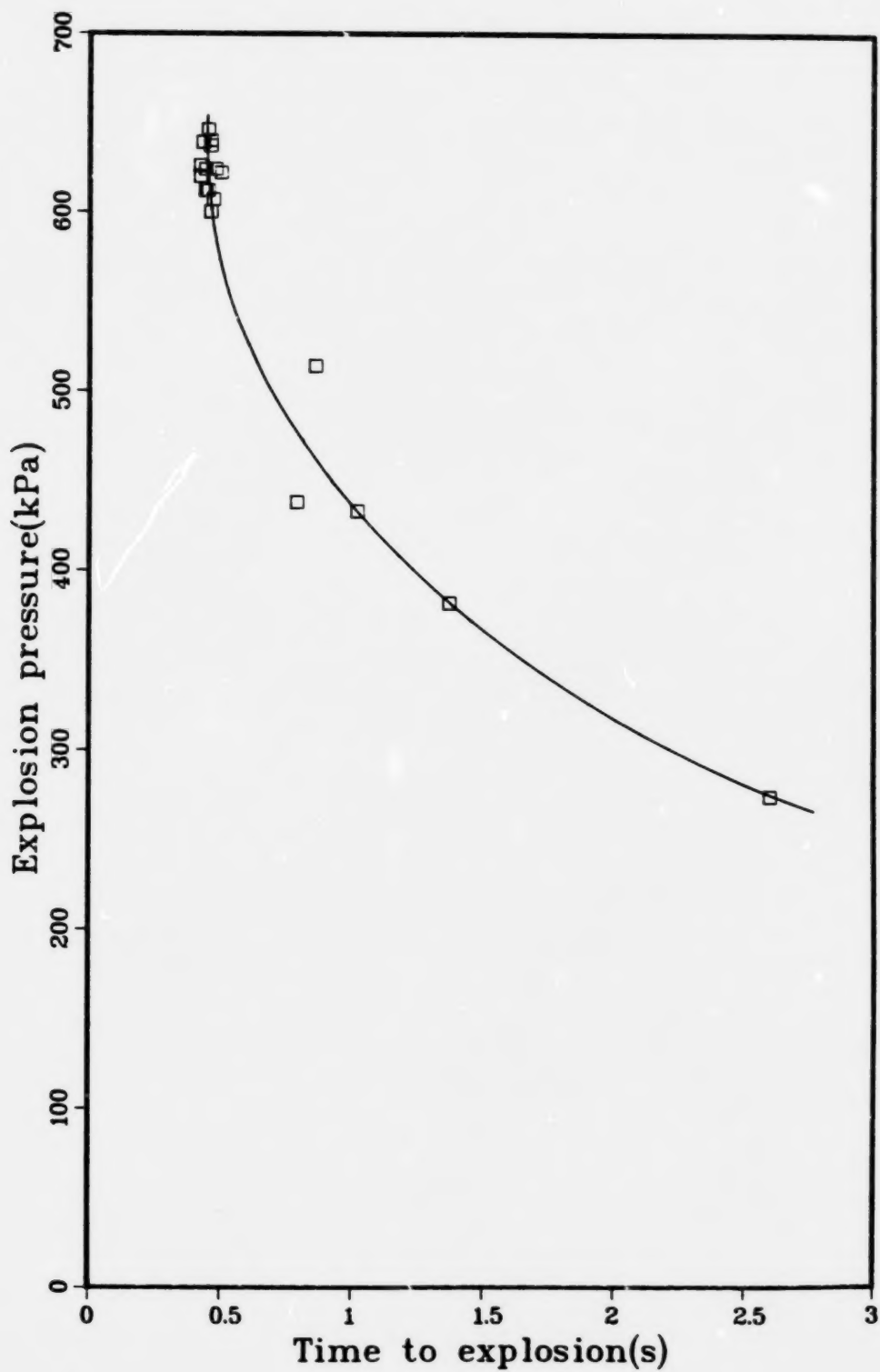


FIG. 11. PERMANENT DEFLECTIONS

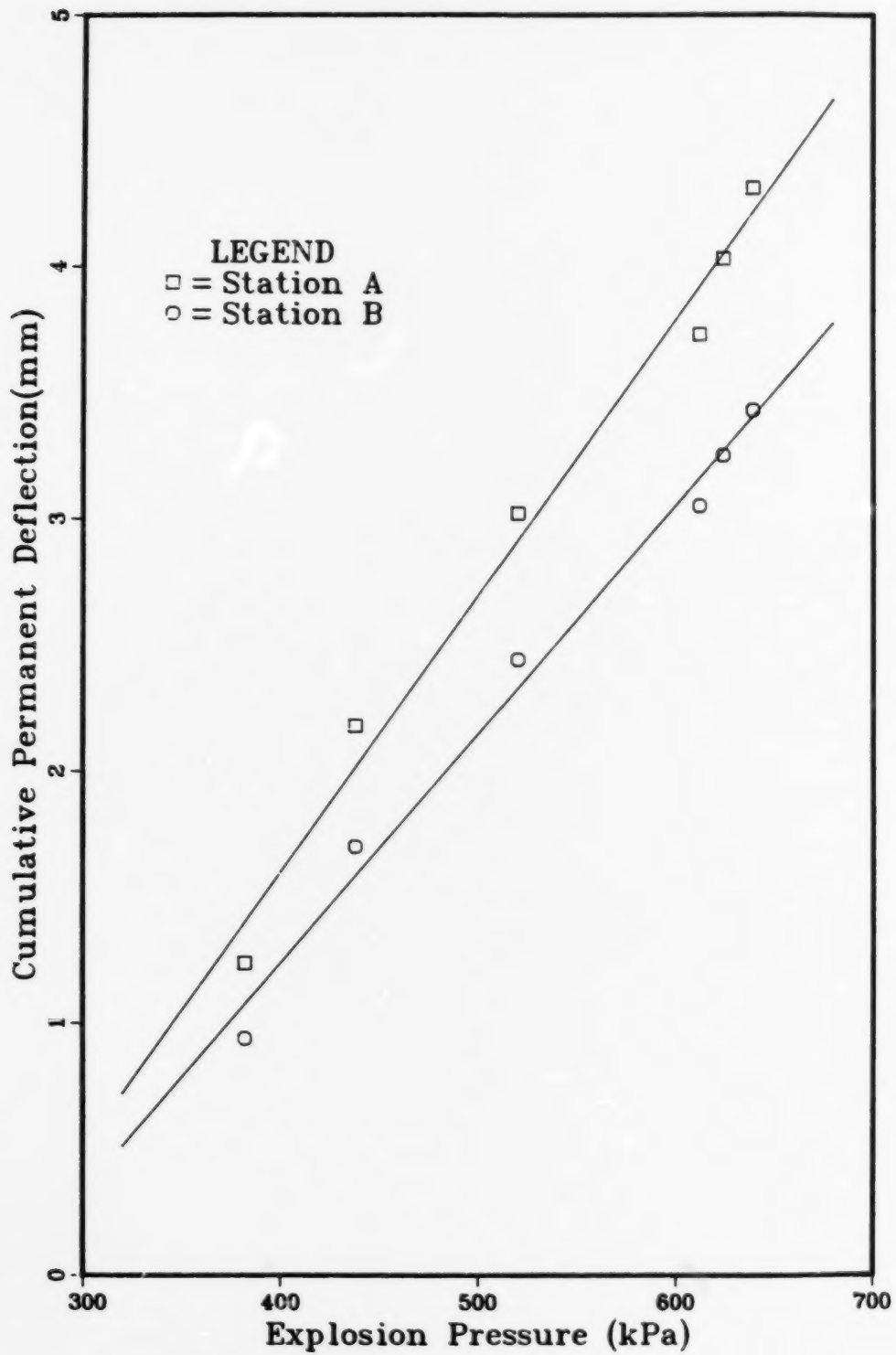


FIG.12.ELASTIC DEFLECTIONS

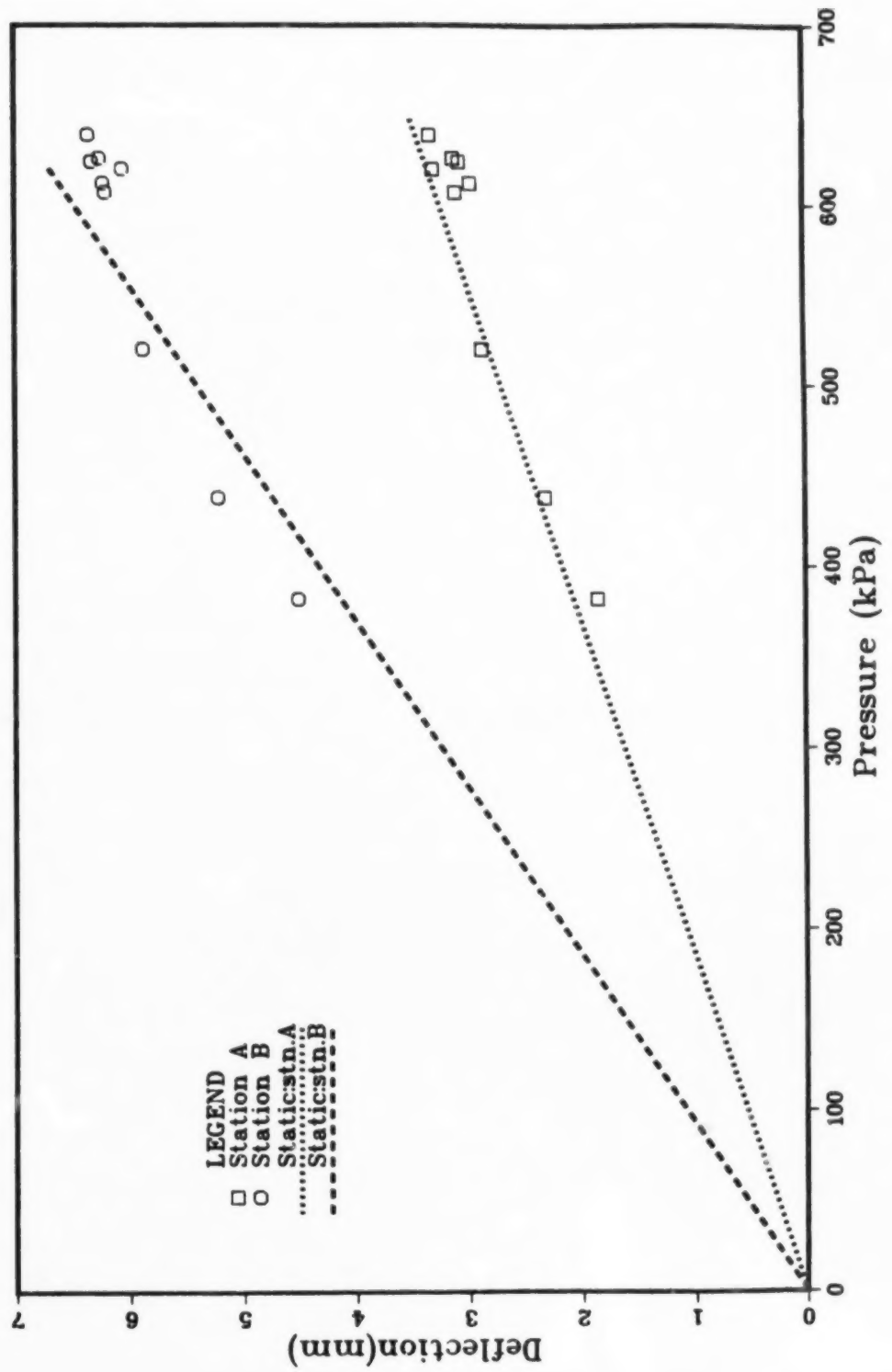


FIG. 13. PERMANENT STRAINS

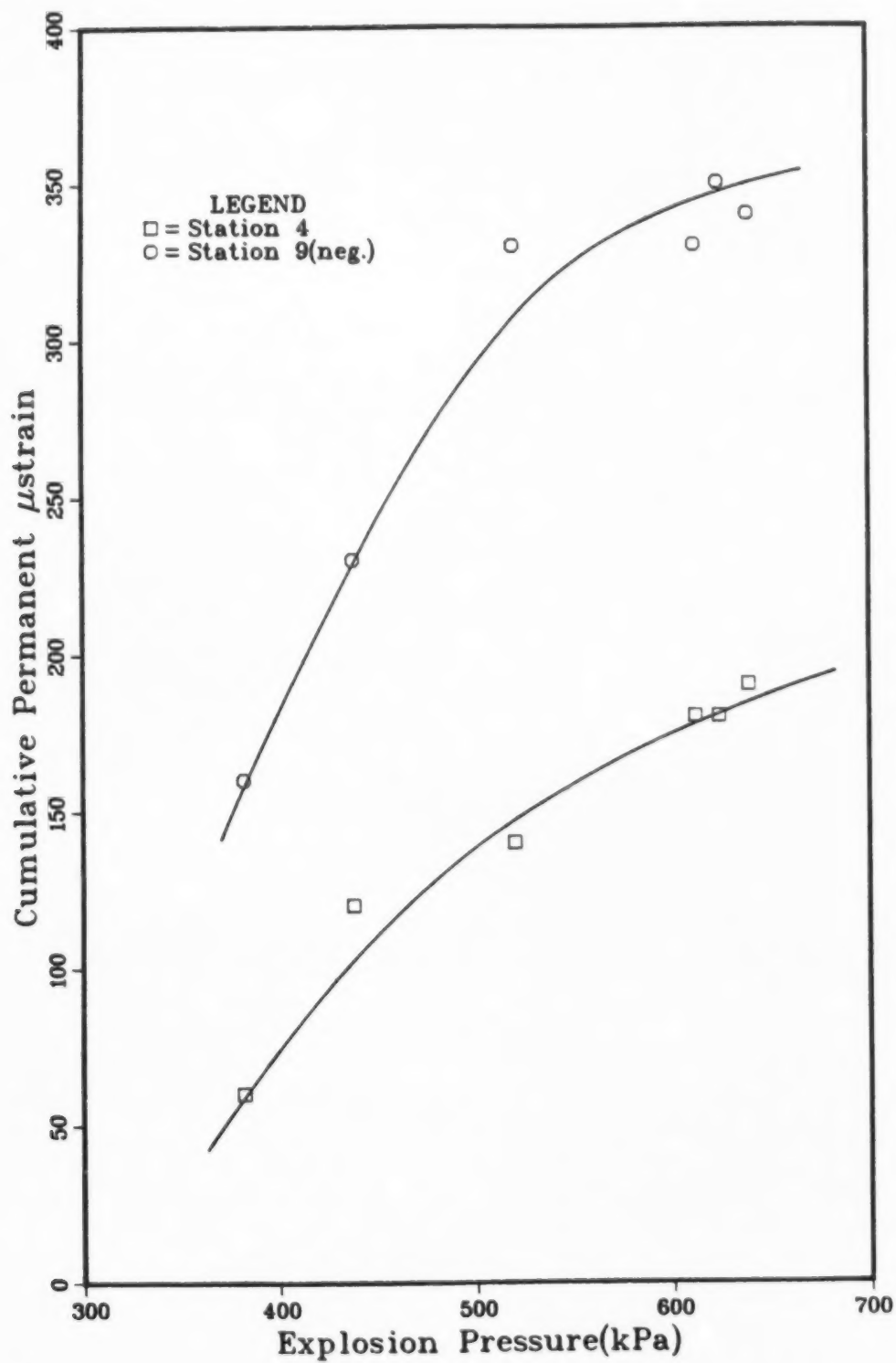


FIG.14. ELASTIC STRAINS

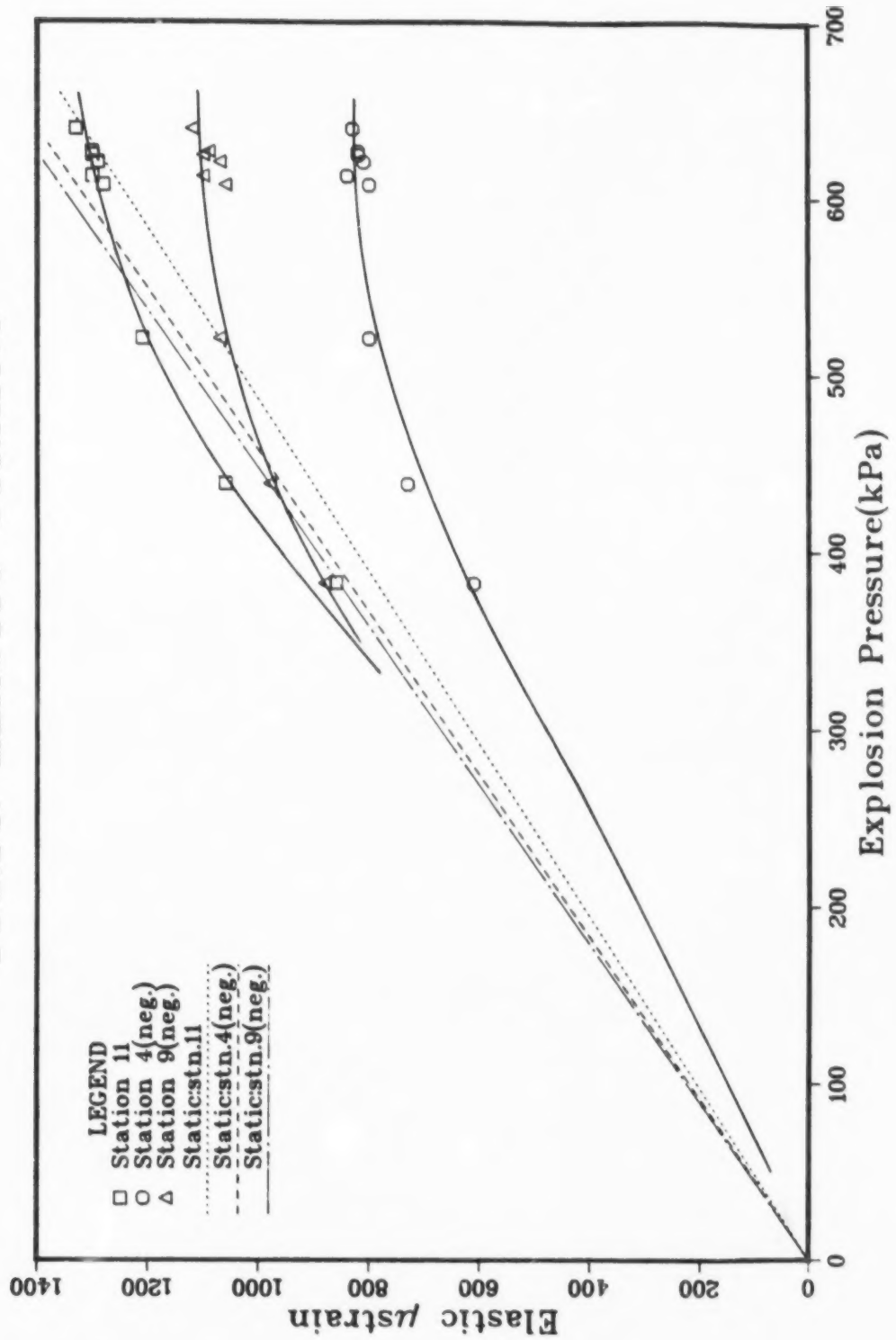


FIG.15.POST EXPLOSION TESTS:DEFLECTIONS

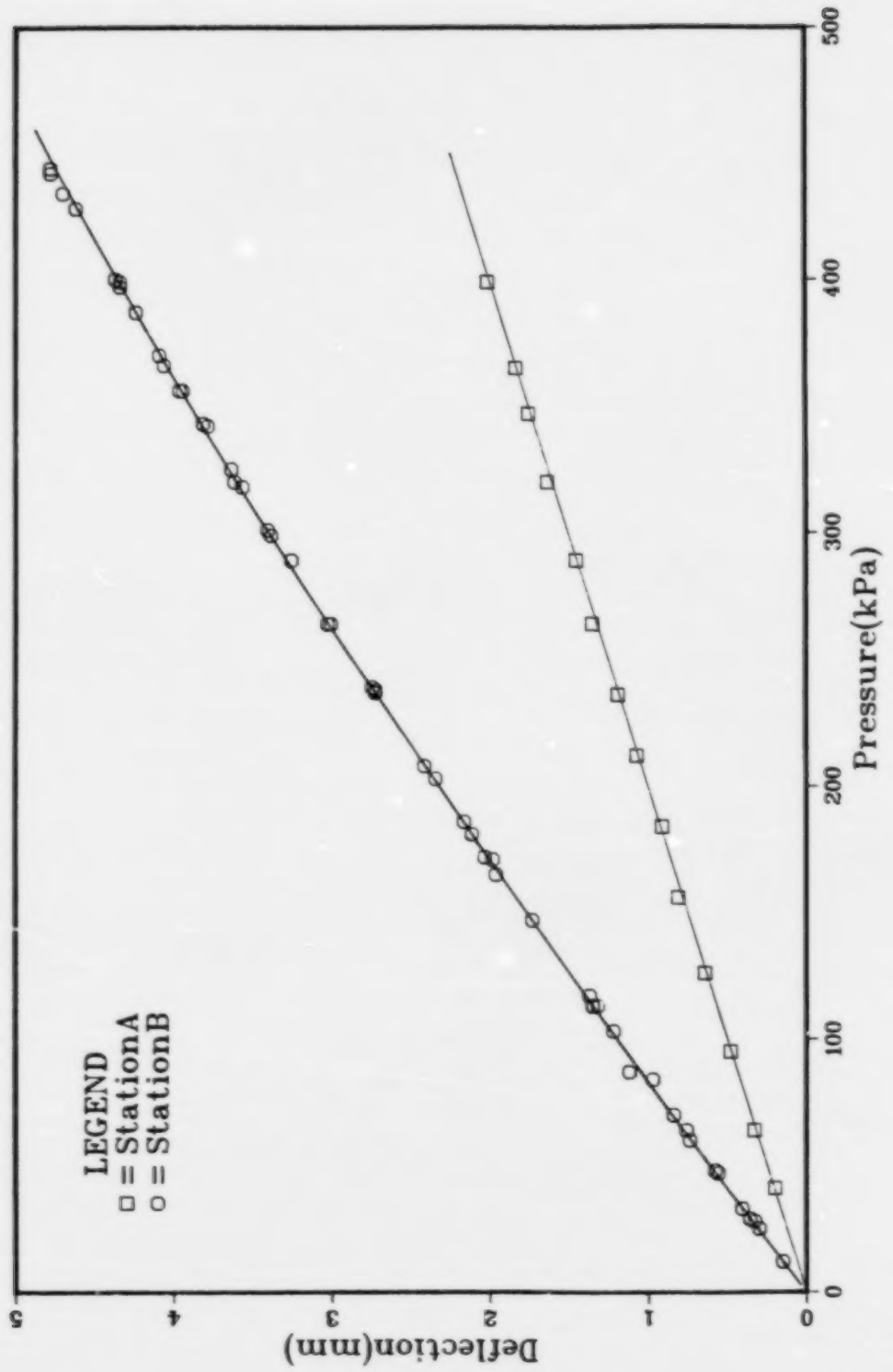


FIG.16.POST-EXPLOSION TESTS:STRAINS

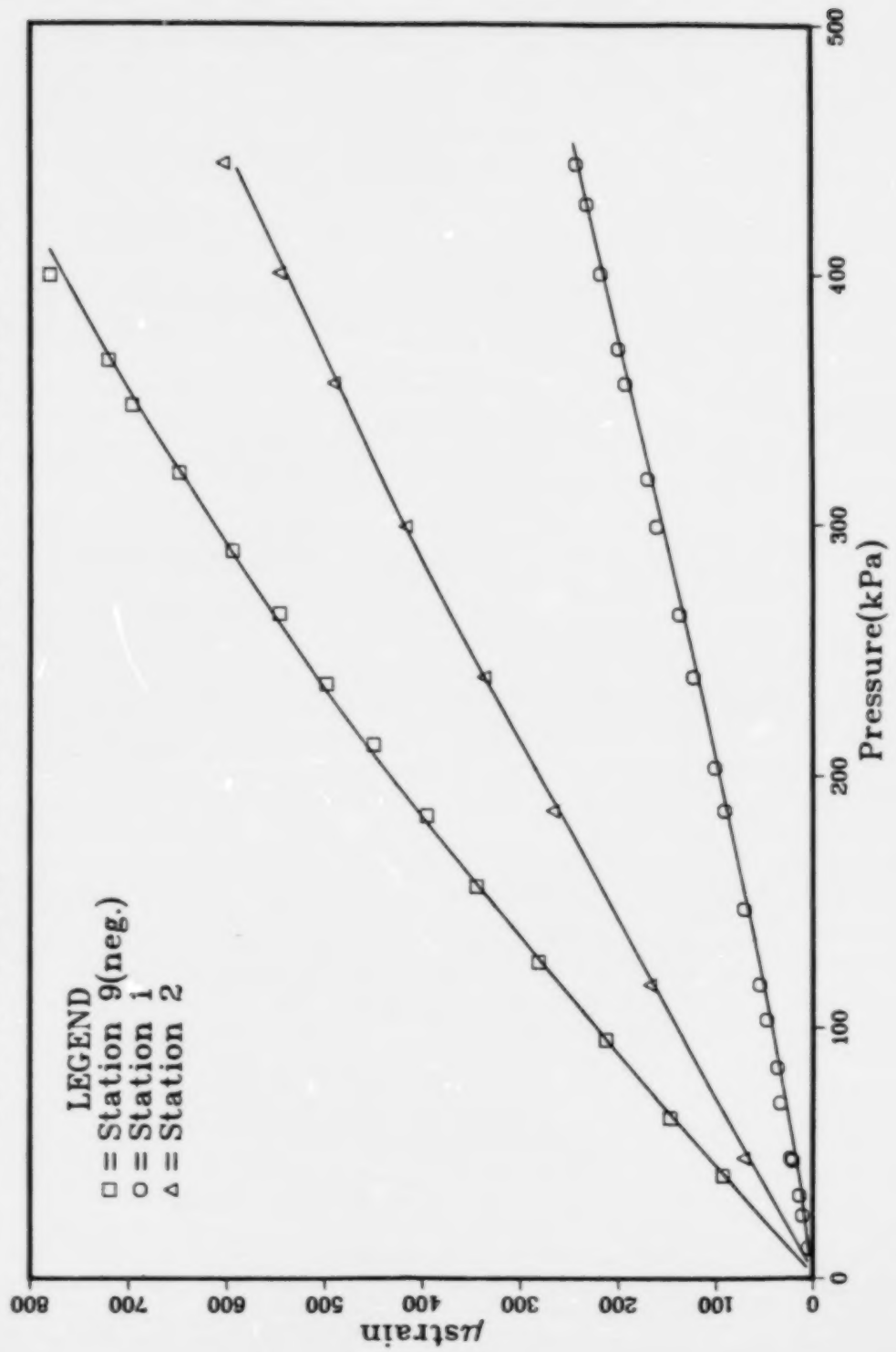


FIG.17.POST-EXPLOSION TESTS:STRAINS

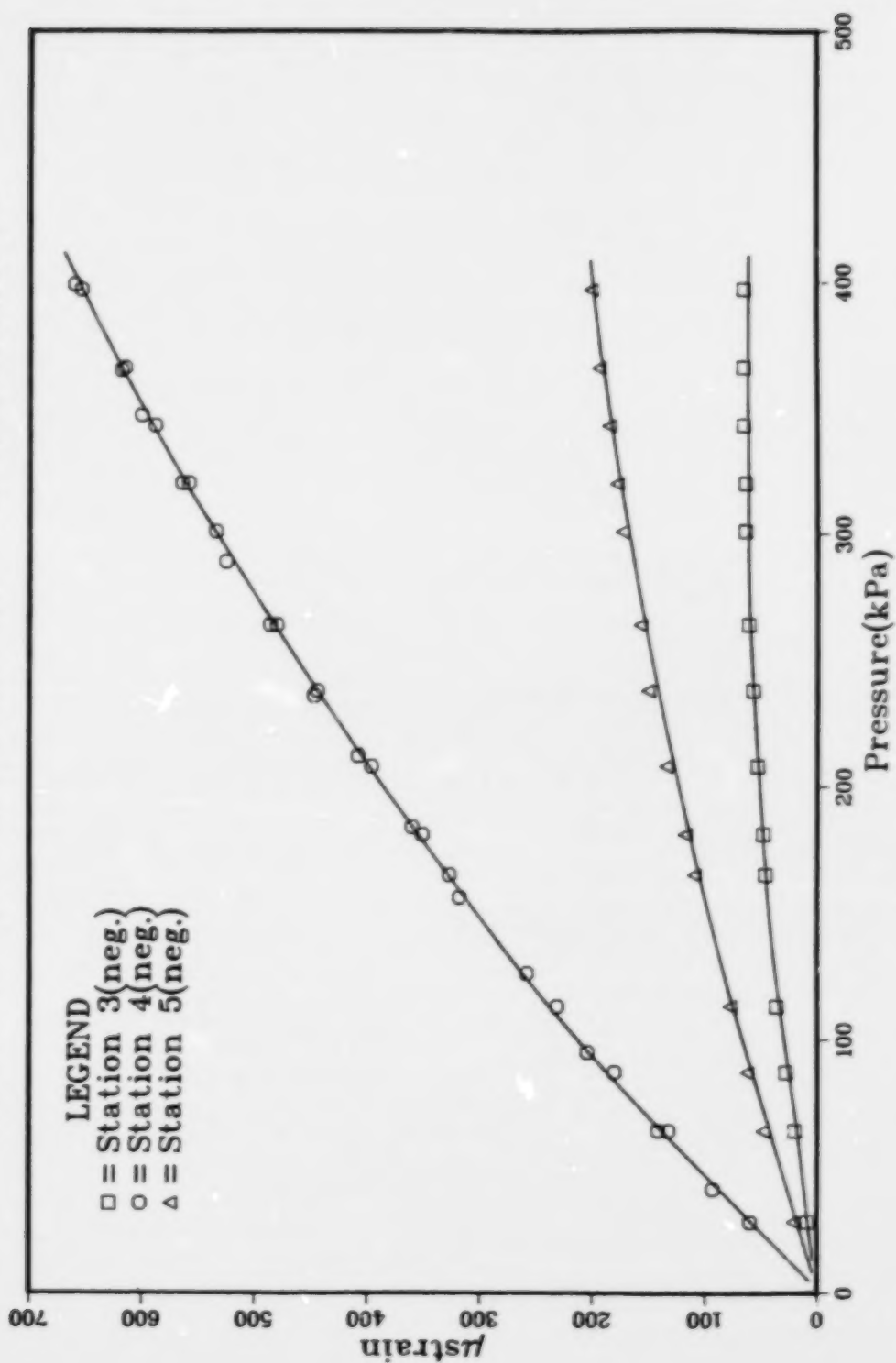


FIG.18.POST-EXPLOSION TESTS:STRAINS

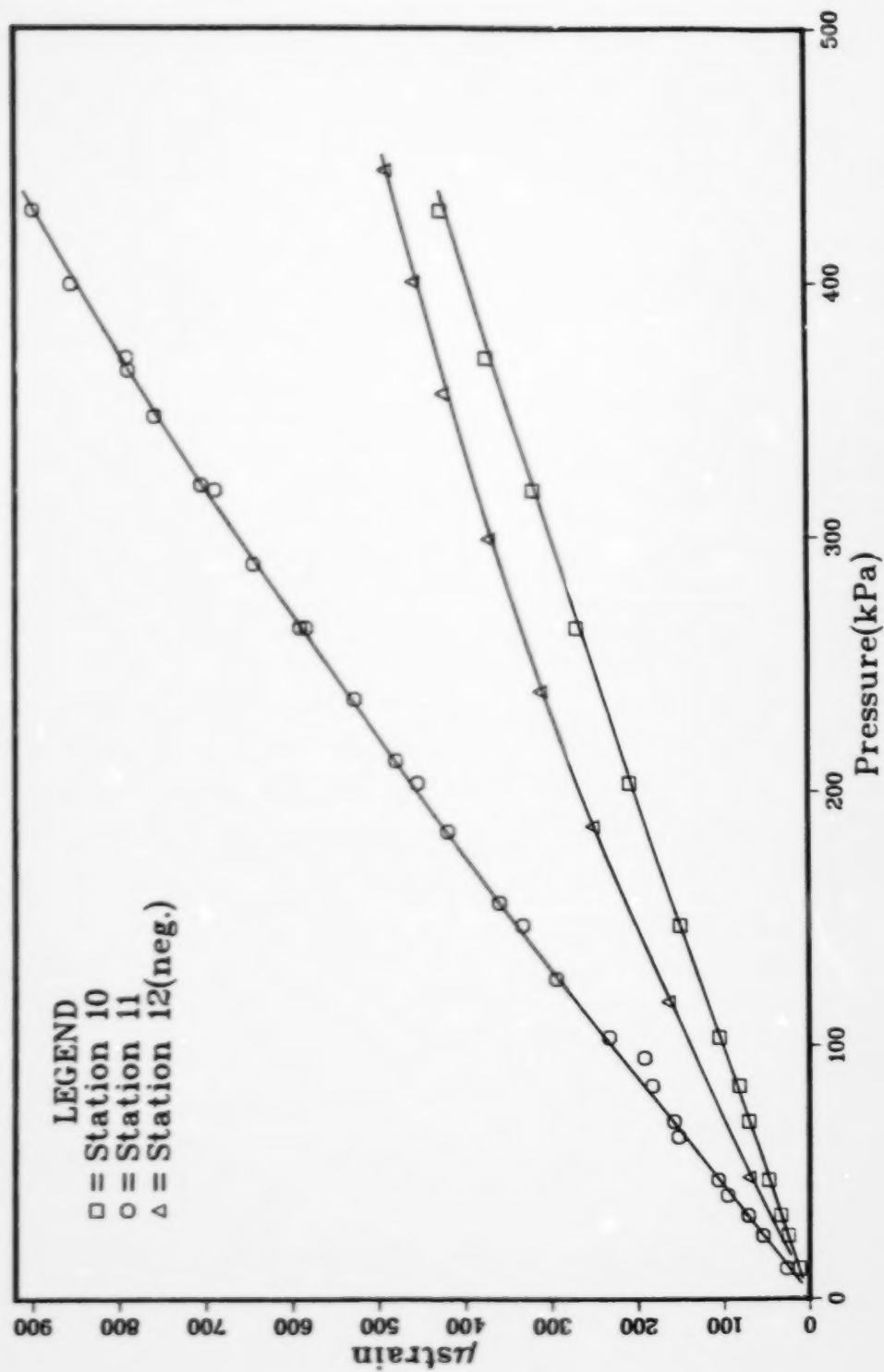


FIG.19.POST-EXPLOSION TESTS:STRAINS

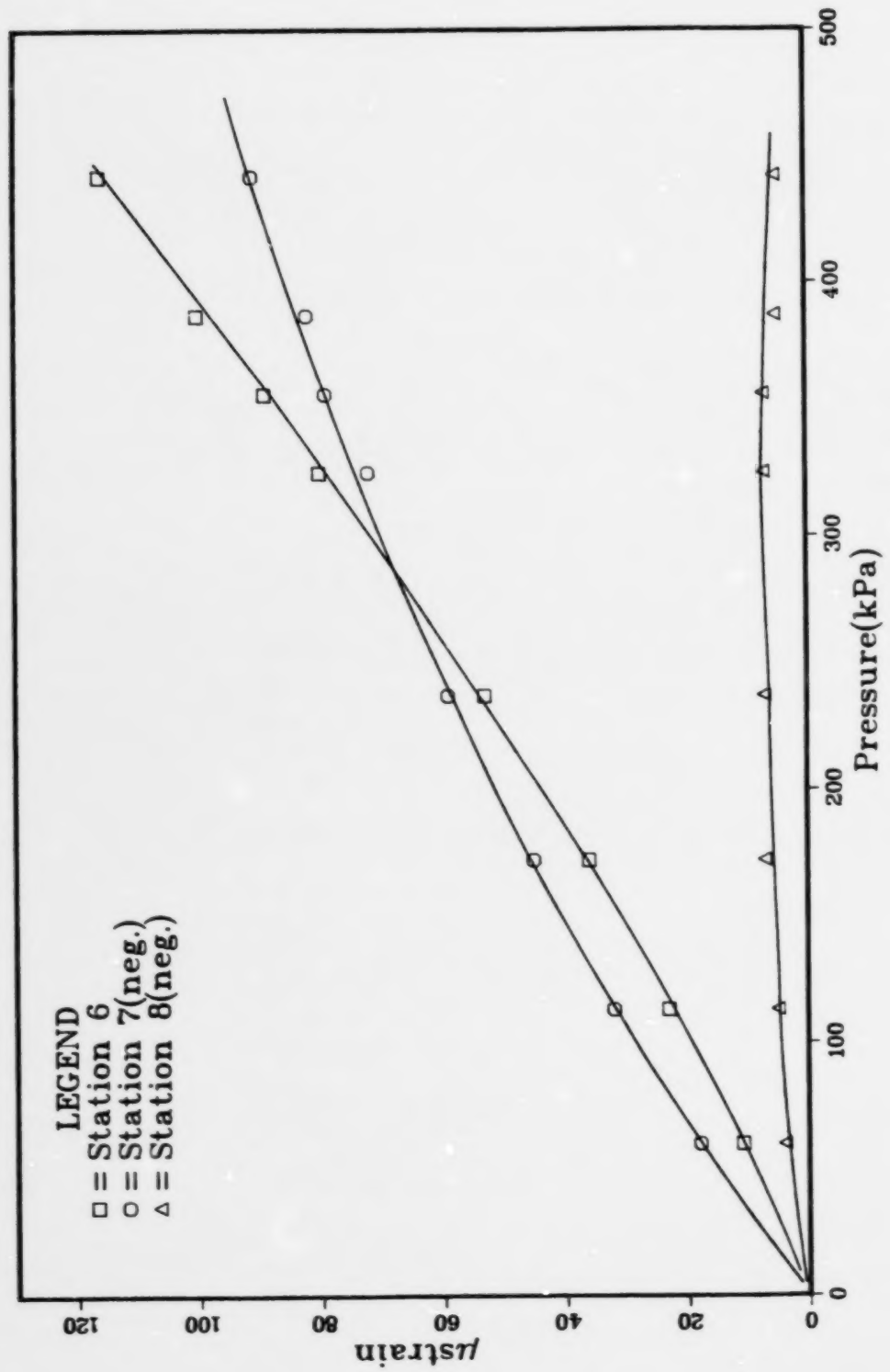


FIG.20.POST--EXPLOSION TESTS:STRAINS

